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Gauge Extension of the Minimal Supersymmetric Standard Model

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Outline:

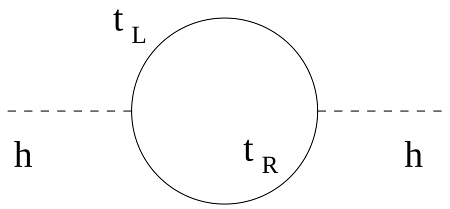
1. Introduction: The MSSM Today
2. The NMSSM and its limits
3. Supersymmetric Topflavor
4. EW Precision Data
5. The Lightest Higgs Mass
6. Selected Phenomenology
7. Outlook

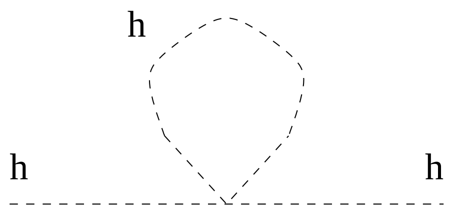
Minimal Supersymmetric Standard Model

- Hierarchy Problem!
- Higgs **doublet** mass^2: m_Φ^2 sets the weak scale:

$$v^2 \quad = \quad \frac{m_\Phi^2}{\lambda} = (246\ \ \mathrm{GeV})^2$$

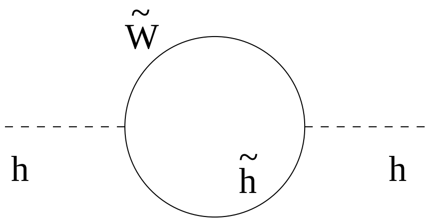
- But it is unstable (quadratically sensitive) to quantum corrections:

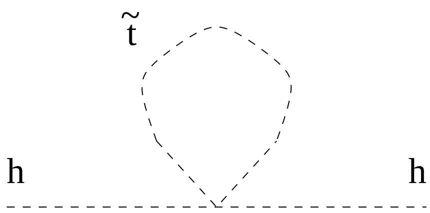




$$\delta m_\Phi^2 \quad \sim \quad \frac{g^2}{16\pi^2}\Lambda^2$$

- SUSY stablizes the hierarchy:



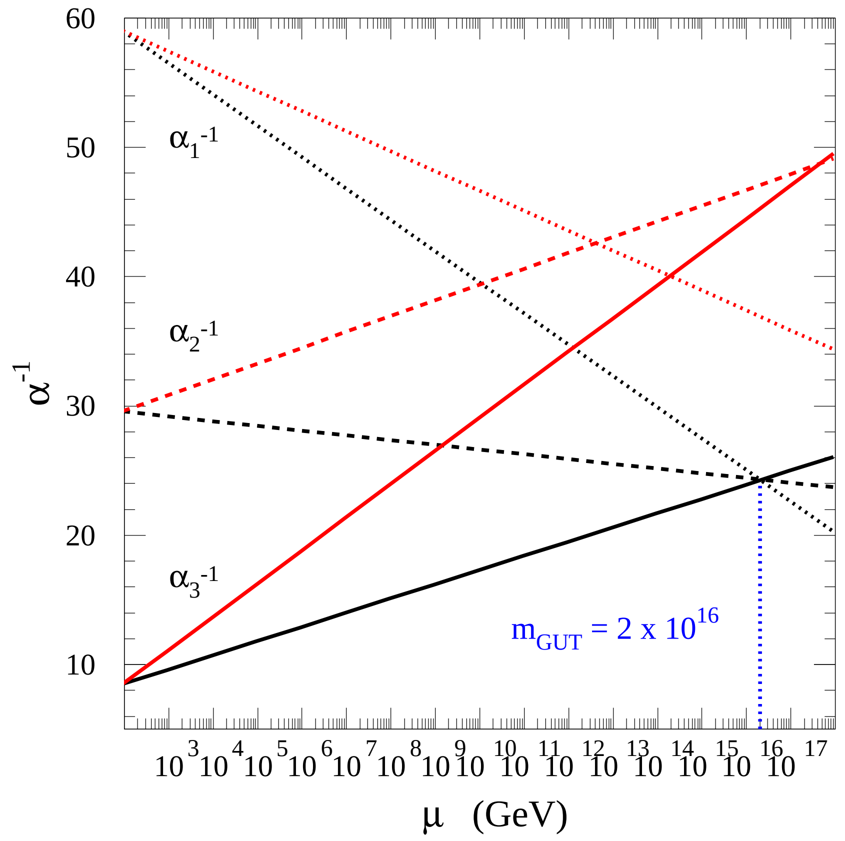


$$\delta m_\Phi^2 \quad \sim \quad \frac{g^2}{16\pi^2} M^2 \log\frac{\Lambda^2}{M^2}$$

- Sensitivity to $\Lambda^2 \ \Rightarrow\ $ sensitivity to M^2.

Grand Unification

- With the SM field content, extrapolating the gauge couplings to high energies shows a **failure** to unify.

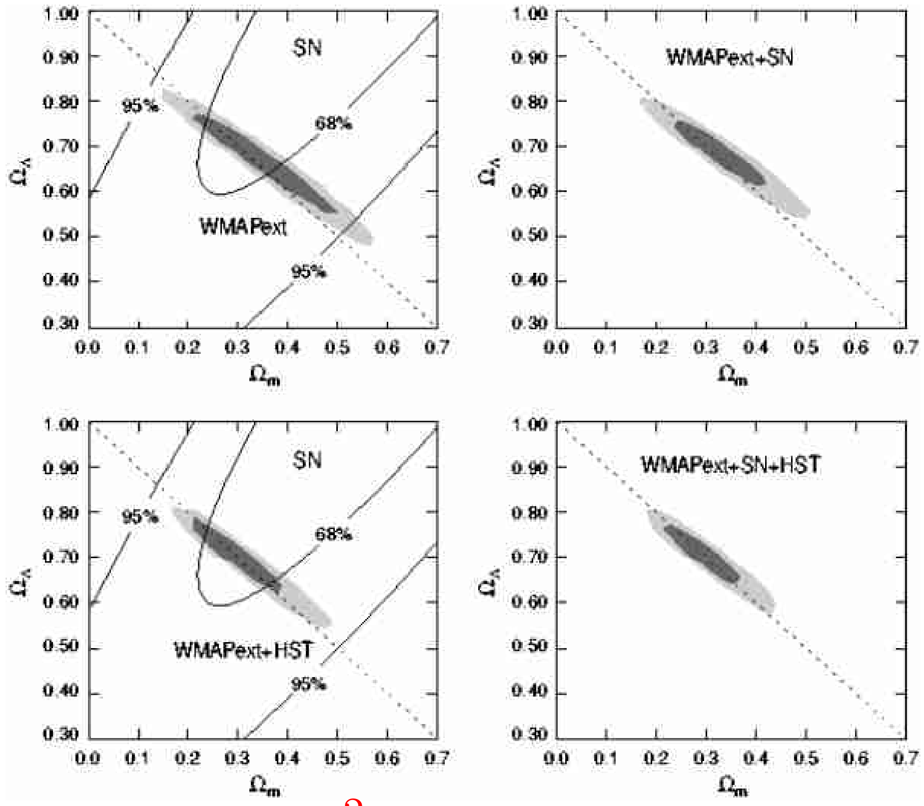


- The MSSM, with SUSY masses at ~ 1 TeV shows a remarkable convergence of the couplings.

- Since the GUT scale $\sim 10^{16}$ GeV, SUSY stabilizes the GUT-weak hierarchy.

Dark Matter

- Astrophysical observations indicate that a non-relativistic dark component is needed.
- A global fit, including WMAP and Supernova data:



$$\Omega_M h^2 \quad = \quad 0.110 \pm 0.006$$

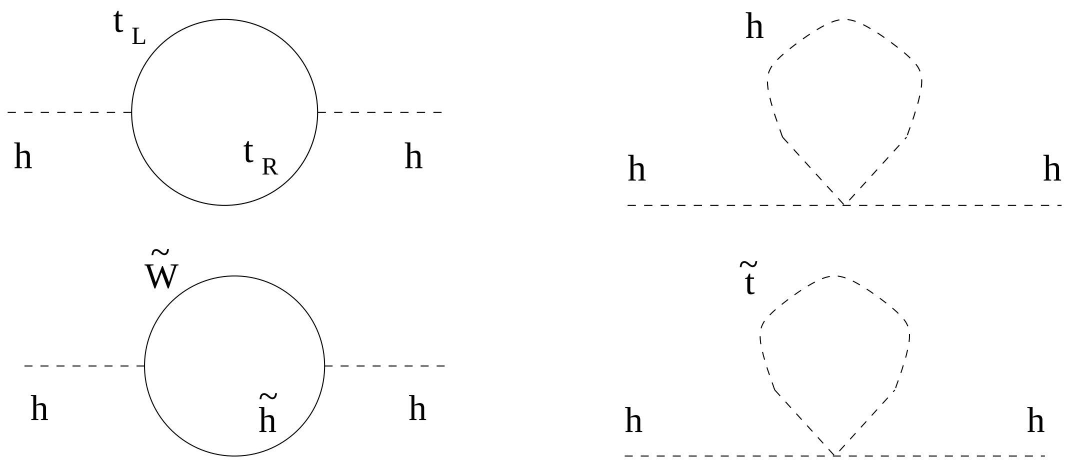
- Structure formation prefers a non-relativistic WIMP.
- The SM has no candidate for these objects.
- The MSSM with R-parity conserved does, if a neutralino or sneutrino is the Lightest Supersymmetric Particle.

Supersymmetry Breaking

- Obviously, SUSY must be broken.
- Soft breaking (through only dimensionful parameters) will preserve an approximation to the solution to the hierarchy problem.
- With no indication of how SUSY is broken, the MSSM has $\gtrsim 100$ free parameters.
- These include:
- Masses for sfermions and gauginos: $M\tilde{\chi}\tilde{\chi}$.
- A-terms: $A_Q H\tilde{Q}\tilde{U}$.
- Masses for Higgs doublets: $B\mu\epsilon_{ij}H_1^i H_2^j$ + h.c.
- These must be chosen such that we are consistent with direct searches, indirect constraints, etc.
- Throughout this talk I will remain agnostic about how SUSY is broken.

Fine-tuning

- The Higgs doublet mass(es) are corrected at one-loop by the top, gauge bosons, and the Higgs.



- The physical masses are the sum of the tree-level piece plus the one loop contributions.

$$m_\Phi^2 \quad \sim \quad (m_\Phi^2)_0 + \frac{g^2}{16\pi^2} M^2 \log\left(\frac{\Lambda}{M}\right)$$

- **Naturalness** demands that these two (a priori independent) contributions are roughly the same size as the sum itself.

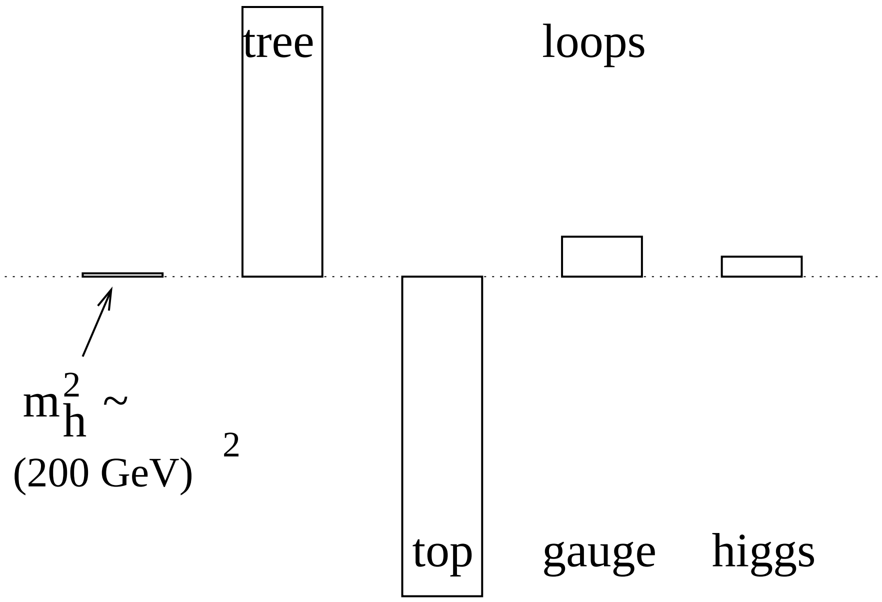
- We don't know the physics that determines the tree level mass, or the SUSY masses. But we do know the sum must be the EWSB scale $v^2 = m_\Phi^2 / \lambda$.

The Little Hierarchy

- A measure of fine-tuning is given by:

$$\frac{\frac{g^2}{16\pi^2} M^2}{v^2}$$

- How small is too small is a matter of personal taste. I start to worry when it gets to the per cent level.
- This is what little Higgsers call the "Little Hierarchy problem". i.e. M. Schmaltz, Λ = 10 TeV:



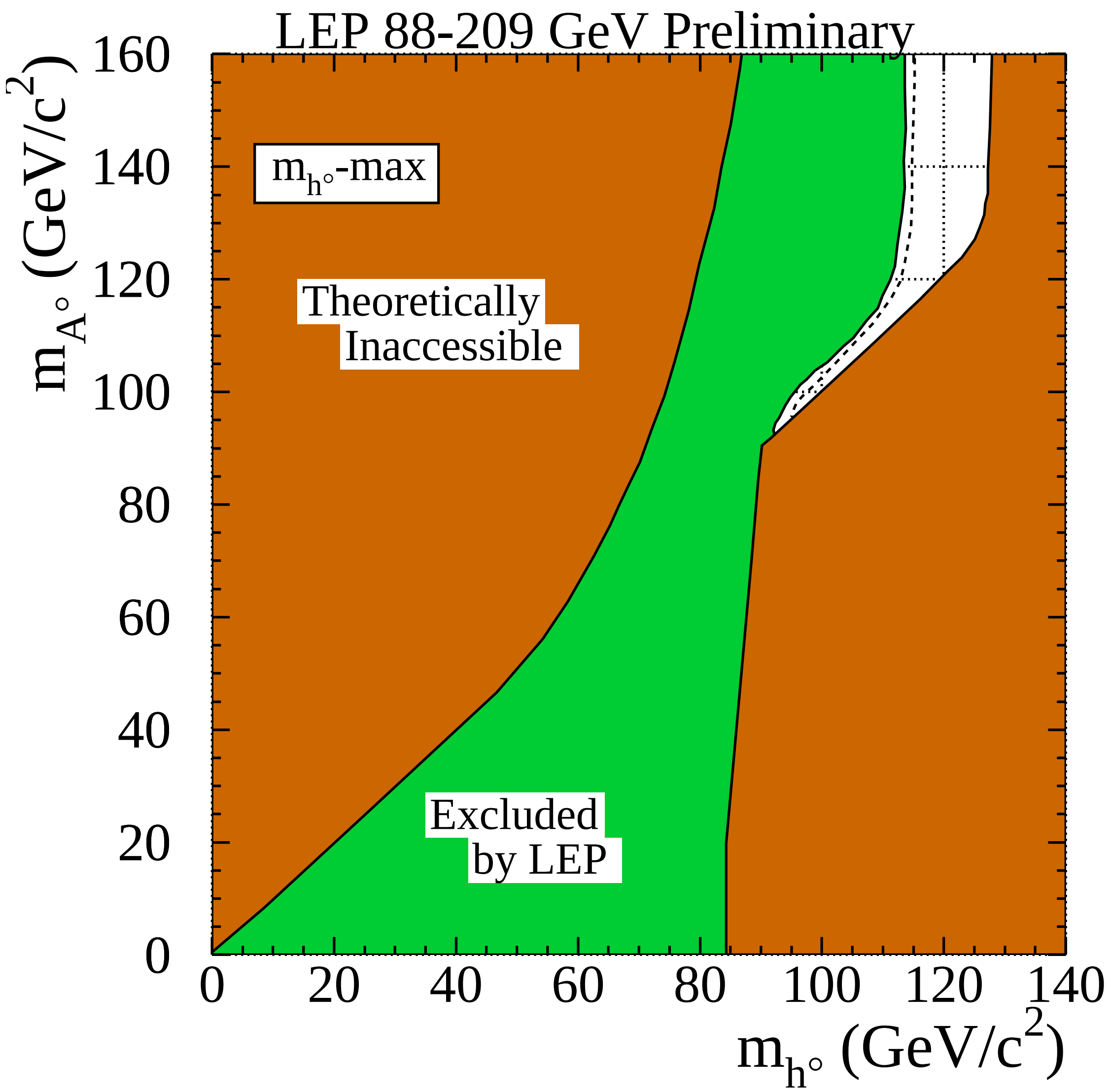
- The biggest loop is top. Fine-tuning less than 10% requires the stop sector to have masses $\lesssim$ **TeV**.

SUSY Light Higgs Mass

- The MSSM has two Higgs doublets.
- They have masses both supersymmetric (μ) and SUSY-breaking (m_1^2, m_2^2, $B\mu$).
- After EWSB, there are two CP even Higgs, a CP-odd Higgs, and a pair of charged Higgs in the spectrum.
- For EWSB, there must also be quartic interactions.
- In the SM, the Higgs quartic λ is a free parameter. After EWSB the Higgs particle mass is $m_h^2 = \lambda v^2$.
- Remarkably, in the MSSM the quartic is NOT a free parameter. It is given at tree level by D-terms of electroweak gauge couplings:
$$\lambda^2 \quad = \quad g_Y^2 + g_W^2$$
- This results in (for $m_A \gg m_h$)
$$m_h^2 = \lambda \;\; v^2 \cos^2 2\beta \quad \leq \quad M_Z^2$$
- At one loop, there are contributions from top/stop:
$$\delta m_h^2 = \frac{3m_t^4}{8\pi^2 v^2}\left[\log\frac{m_{\tilde{t}}^2}{m_t^2} + \text{stop mixing}\right]$$

LEP II

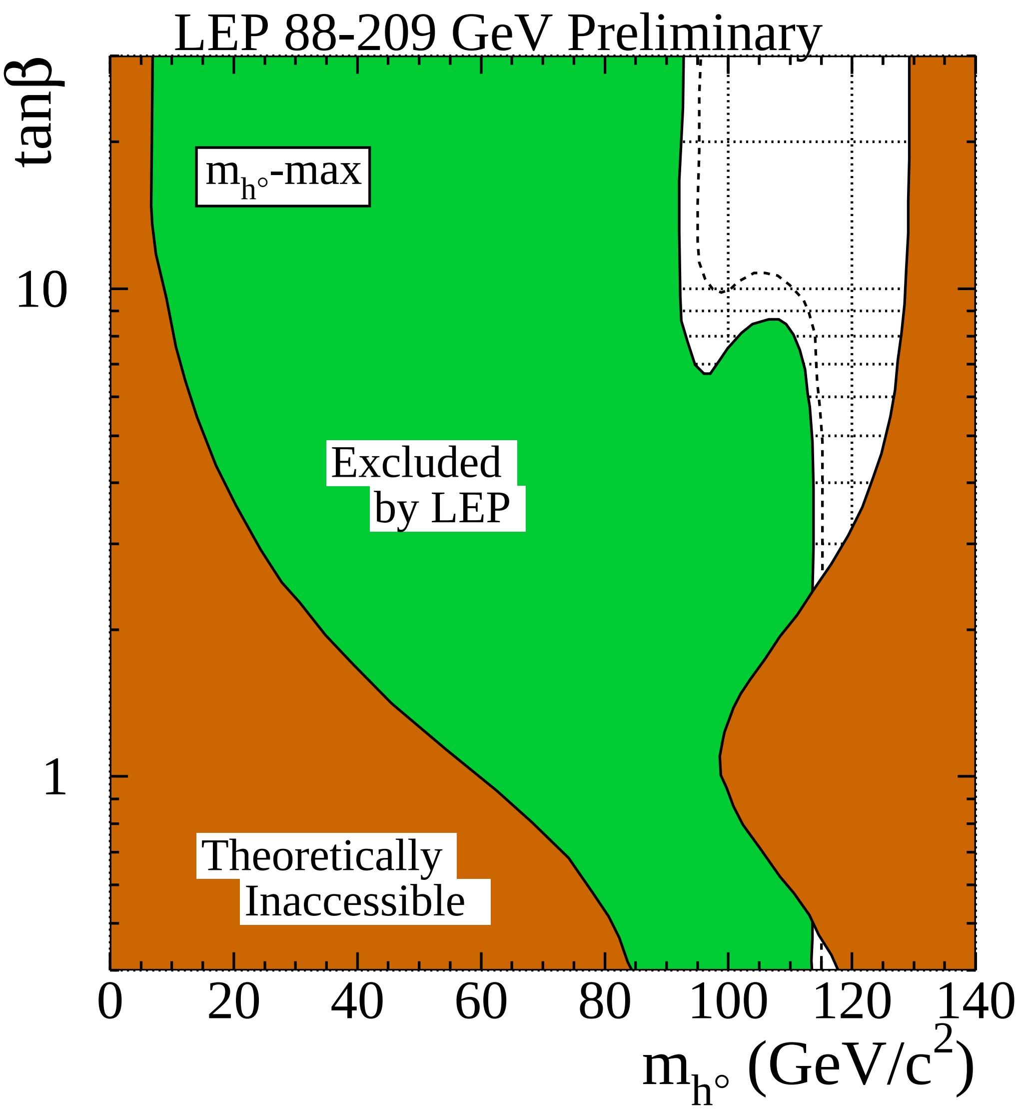
- LEP-II rules out $m_h^{(SM)} \lesssim 115$ GeV.



- The boundary on the right is the MSSM upper limit on m_h, assuming $m_{\tilde{t}} = 1$ TeV and maximal mixing.
- Maximal mixing requires $\mathbf{A_t \sim 2.5}$ **TeV**.
- Dashed curve: hypothetical exclusion if one assumes SM predictions for backgrounds.

LEP II: Alternate Perspective

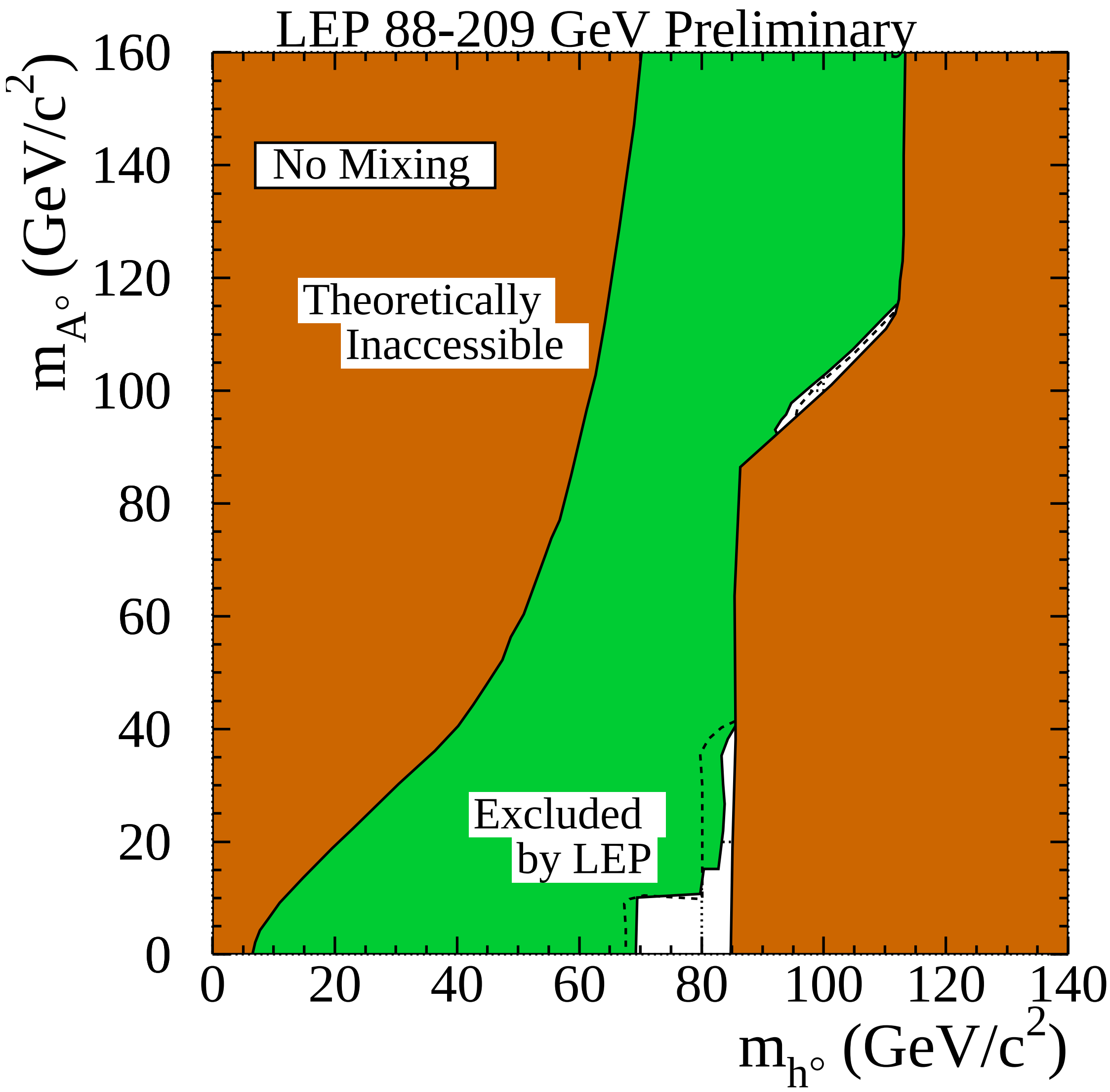
- LEP-II rules out $m_h \lesssim 115$ GeV.



- The small corner at low $\tan\beta$ is a strange region with very light $H^{\pm}$.

Stop Mixing

- Things get worse when the stops are not mixed:



- For $m_{\tilde{t}} \lesssim 1$ TeV, mixing is required.

SUSY Little Hierarchy Problem

- This is the "**SUSY little hierarchy problem**".
- The Higgs quartic is a hard term, so it is unaffected by SUSY breaking.
- m_h can be made consistent with LEP data only through quantum corrections involving soft masses:

$$\delta m_h^2 = \frac{3m_t^4}{8\pi^2 v^2}\left[\log\frac{m_{\tilde{t}}^2}{m_t^2} + \text{stop mixing}\right]$$

- Consistent with LEP-II, $m_{\tilde{t}} \gtrsim 500$ GeV.
- But these also contribute to the Higgs doublet mass, destabilizing the weak scale:

$$\delta m_1^2 \sim \frac{-12y_t^2}{16\pi^2} m_{\tilde{t}}^2 \log\frac{\Lambda^2}{m_{\tilde{t}}^2}$$

- To arrange for v, one must fine tune μ to **% level**:

$$\frac{1}{2}m_Z^2 = -\mu^2 - \frac{m_1^2\tan^2\beta - m_2^2}{\tan^2\beta - 1}$$

- Unlike the usual problems with SUSY (such as flavor), this has nothing to do with the specifics of SUSY-breaking. It is an aspect of the MSSM itself.

NMSSM

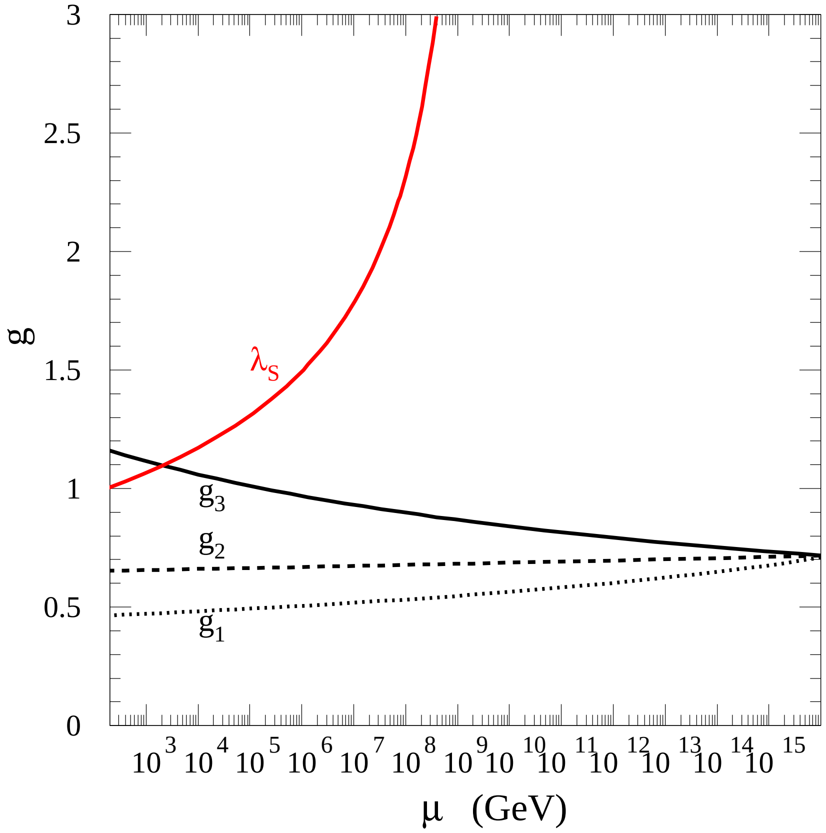
- Next to Minimal Supersymmetric Standard Model.
- We add a singlet superfield S with super-potential:

$$W = \lambda_S S H_1 H_2 + \mu_S S^2 + \ldots$$

- This modifies the effective Higgs quartic:

$$\lambda^2 = g_Y^2 + g_W^2 + \lambda_S^2 \tan^2 2\beta$$

- A free parameter, λ_S, controls the light Higgs mass.
- However, λ_S blows up in the UV:

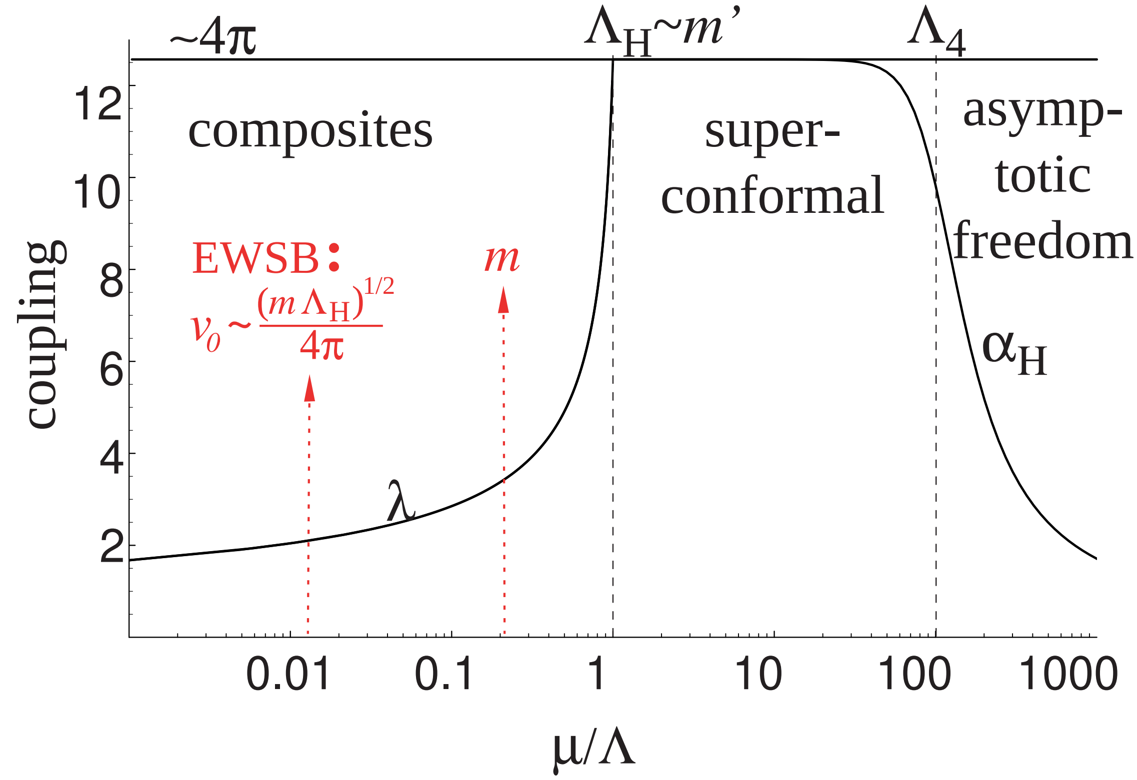


- Perturbative to M_{GUT}, $m_h \lesssim 150$ GeV.
- Otherwise, strong coupling at low scales.

SUSY Fat Higgs Model

[Harnik, Kribs, Larson, Murayama]

- The SUSY fat Higgs model interprets the Landau pole of the NMSSM as a compositeness scale.



- Matter is arranged so it transitions to a sCFT, maintaining control of coupling unification.

- EWSB is divorced from SUSY breaking:

$$W = \lambda N \left(H_1 H_2 - v_0^2\right)$$
$$v_0^2 \sim m\Lambda_H/(4\pi)^2$$

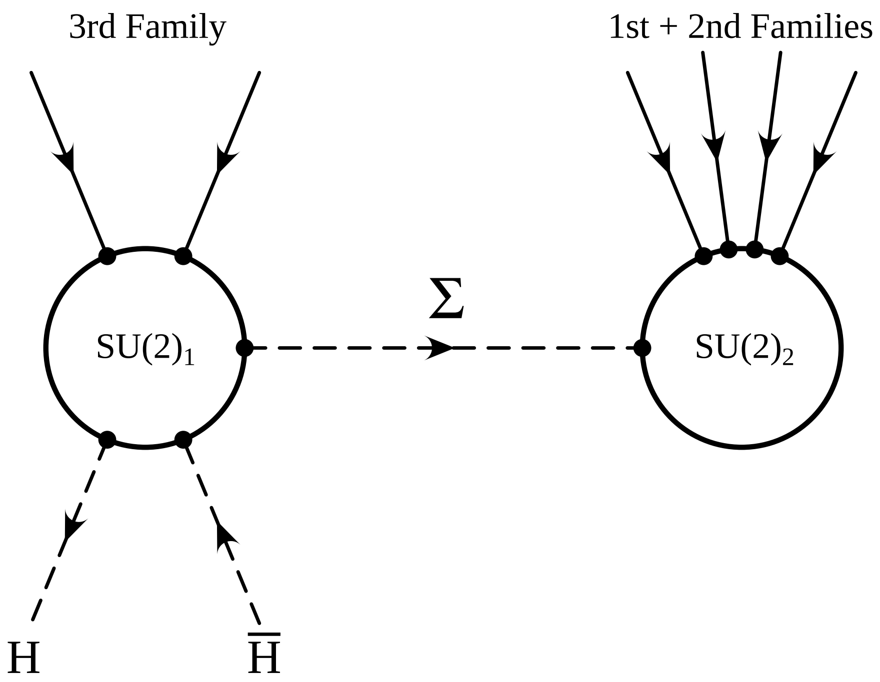
- Raises the question why SUSY breaking is $\sim v$.

Gauge Extensions

- The NMSSM worked as a means to raise the Higgs mass, but the requirement that all couplings are perturbative to the GUT scale limits its effectiveness.
- What would be preferable is a coupling which is strong at v and flows weaker at the GUT scale.
- Non-Abelian gauge theories have this property.
- I will explore an $SU(2)$ gauge extension of the MSSM which increases the Higgs mass.
- Our desire is to raise the Higgs mass, stay consistent with precision data, and maintain naturalness.
- While I won't have very detailed requirements for the soft masses of MSSM fields, I would like them to be small but consistent with direct searches (so a few hundred GeV).

$SU(2)_2$: Topflavor

- Our model has electroweak gauge group $SU(2)_1 \times SU(2)_2 \times U(1)_Y$.



- The "usual" $SU(2)_L$ is the diagonal combination.

- MSSM fields split between the two $SU(2)$ groups:

$$SU(2)_1 \quad : \quad H_1, H_2, Q_3, L_3$$

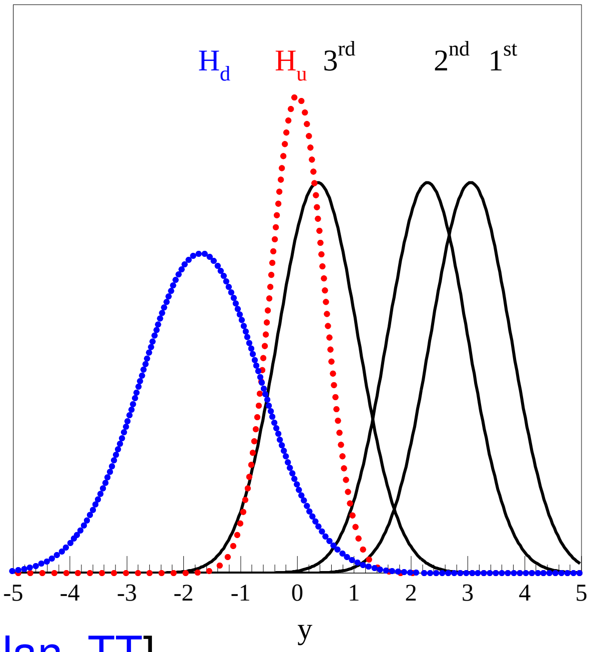
$$SU(2)_2 \quad : \quad Q_1, Q_2, L_1, L_2$$

- A Higgs Σ is a bi-doublet under both $SU(2)$'s.

- This model has been called **Topflavor**: a separate weak interaction for the third family. [Malkawi, TT, Yuan]

$SU(2)_2$

- This looks something like a deconstruction of an extra dimension: [Hill, Pokorski, Wang]



[D.E. Kaplan, TT]

- The D-terms are:

$$\frac{g_1^2}{8}\left(\mathrm{Tr}\left[\Sigma^\dagger\sigma^a\Sigma\right]+H_1^\dagger\sigma^a H_1-H_2\sigma^a H_2^\dagger+\ldots\right)^2$$
$$+\frac{g_2^2}{8}\left(\mathrm{Tr}\left[\Sigma^\dagger\sigma^a\Sigma\right]\right)^2+\frac{g_Y^2}{8}\left(|H_2|^2-|H_1|^2+\ldots\right)^2$$

- Breaking $SU(2)_1\times SU(2)_2\to SU(2)_L$, SUSY will decouple the additional D-term.

- Thus, we introduce a soft mass for Σ of the same order as the $SU(2)\times SU(2)$ breaking scale, u.

$$SU(2)_1 \times SU(2)_2 \to SU(2)_L$$

- We introduce a super-potential for Σ:

$$W = \lambda S \left(\frac{1}{2} \Sigma\Sigma + w^2 \right)$$

- which produces a scalar potential for Σ:

$$V_\Sigma = \frac{1}{2} \lambda w^2 \Sigma\Sigma + h.c. + \frac{|\lambda|^2}{4} |\Sigma\Sigma|^2 + \tilde{m}_\Sigma^2 |\Sigma|^2$$

- resulting in a VEV for Σ

$$\langle \Sigma \rangle = \sqrt{\frac{\lambda w^2 - \tilde{m}_\Sigma^2}{\lambda^2}} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \equiv u\mathbf{1}$$

- The low energy gauge coupling is:

$$\frac{1}{g^2} = \frac{1}{g_1^2} + \frac{1}{g_2^2}$$

- We can introduce a mixing angle in analogy with the weak theory:

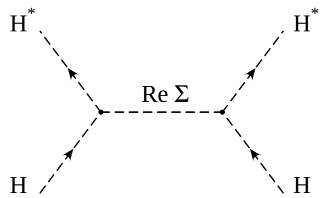
$$g_1 = \frac{g}{\sin\phi}; g_2 = \frac{g}{\cos\phi}$$

- Note that strong coupling results for either $\sin^2\phi \equiv s^2 \to 0$ or 1.

$$M_{W'}^2 = M_{Z'}^2 = \frac{1}{2} \frac{g^2}{s^2 c^2} u^2 \left(1 + c^2 \frac{v^2}{u^2} + \ldots \right)$$

Higgs Quartic

- Under the unbroken $SU(2)$, Σ contains a complex triplet and a complex singlet .
- Im(Σ) is eaten by W', Z'.



- Integrating out Re(Σ) yields:

$$\frac{g^2}{8}\Delta\left(H_1^\dagger\sigma^a H_1 - H_2\sigma^a H_2^\dagger\right)^2 + \frac{g_Y^2}{8}\left(|H_2|^2 - |H_1|^2\right)^2$$

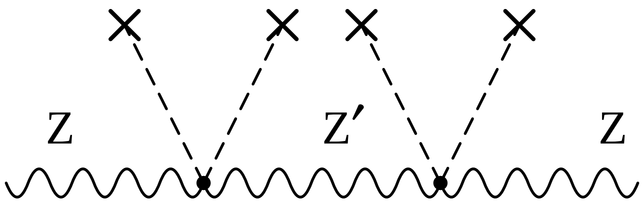
- The $SU(2)$ D-term is modified by:

$$\Delta \equiv \frac{1+\frac{\tilde{m}_\Sigma^2}{M_{Z'}^2 s^2}}{1+\frac{\tilde{m}_\Sigma^2}{M_{Z'}^2}}$$

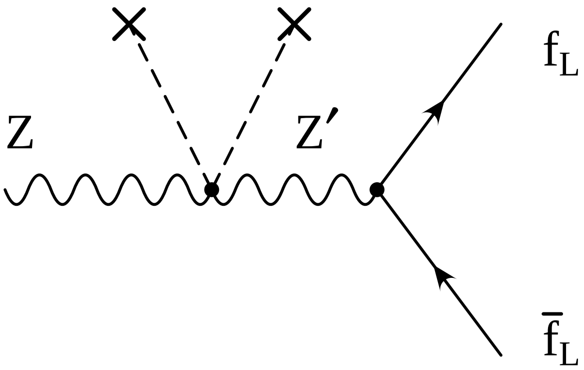
- $\Delta \longrightarrow 1$ is the MSSM limit.
- To maximize the increase in m_h, we want:
  - Coupling g_1 strong (s small).
  - $M_{Z'}$ as small as allowed.
  - $\tilde{m}_\Sigma$ as large as possible.
- Below u, this looks like a hard breaking of SUSY in the Higgs quartic sector.

Precision Electroweak Constraints

- This theory has W'/Z' which prefers to couple to the third family.
- For $v \ll u$, we can treat v as an insertion.
- This is equivalent to integrating out the W'/Z'.
- Corrections to precision observables:
  - Oblique corrections to the W/Z masses:



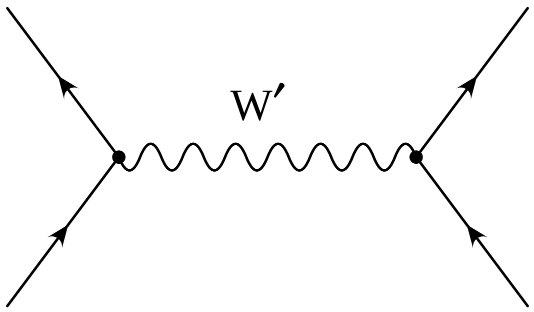
  - Non-oblique corrections to W/Z-$\bar{f}_L$-f_L:



  - These distinguish the 3rd generation.
- Both are proportional to $x \equiv v^2/u^2$.

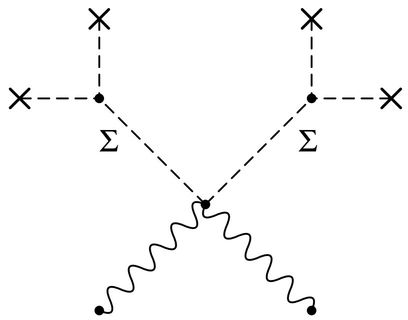
Precision Electroweak Constraints

- Non-oblique contributions to G_F:



- This corrects the extracted G_F by order v^2/u^2.

- In addition, there is the heavy triplet, which through EWSB obtains a small VEV.



- This is an oblique contribution to the W (but not Z) masses which induces a non-zero ΔT:

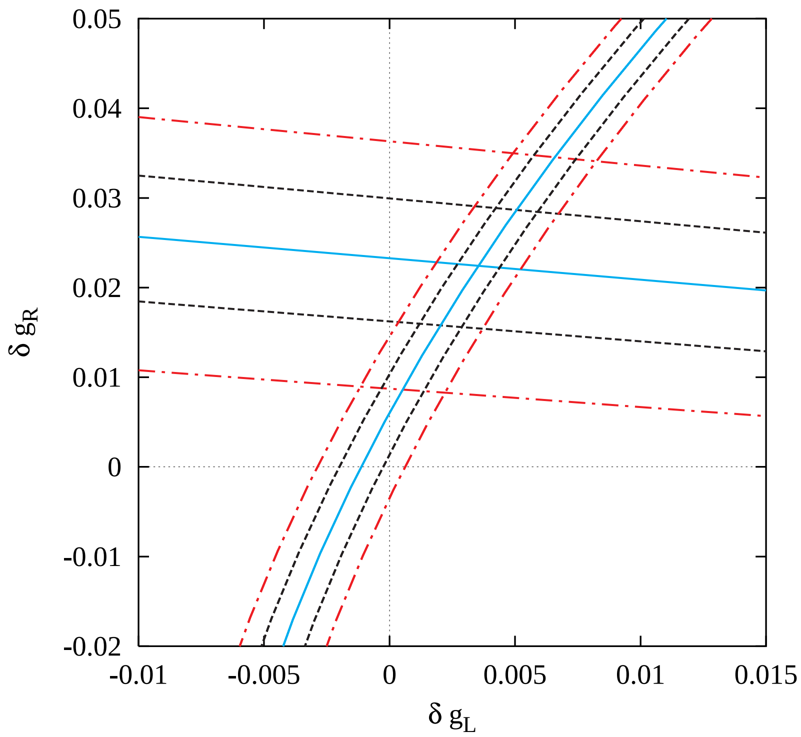
$$\Delta T \sim \frac{4\pi}{s_W^2 c_W^2} \frac{1}{s^4} \frac{M_W^2 u^2}{(\tilde{m}_\Sigma^2 + u^2)^2}$$

- This positive ΔT helps compensate larger m_h.

- We include all of these corrections in a global fit to LEP/SLD data.

b Couplings

- Strongest constraints are from τ/b couplings. I.e., A^b_{FB} and $R_b \Rightarrow Z$-$\bar{b}_{L/R}$-$b_{L/R}$.
- In the plane of g_L-g_R:



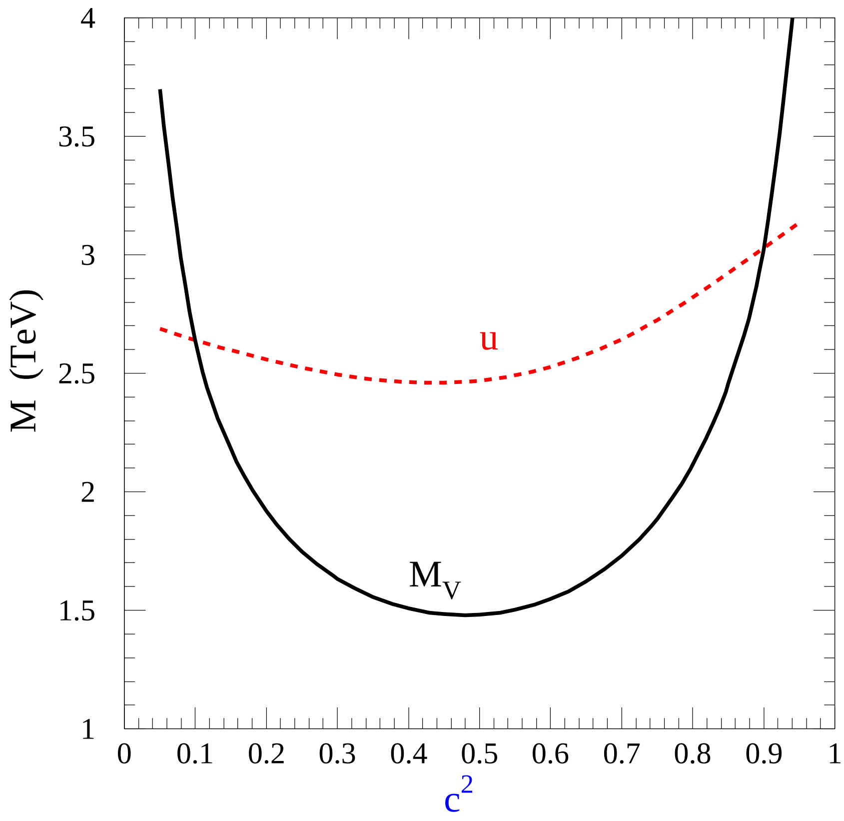
[Choudhury, TT, Wagner]

- $\delta g \sim (e/s_W c_W) v^2/u^2 \lesssim 10^{-3} \Rightarrow u \gtrsim 2.5$ TeV.
- There are corrections from the super-partners.
- These are very model-dependent, so we do not include them.

Observable	**Experiment**	**Topflavor**	**Pull**
Γ_Z	2.4952 ± 0.0023	2.49581	-0.265542
$\alpha_S(MZ)$	0.118 ± 0.003	0.118217	-0.072334
R_e	20.804 ± 0.05	20.7423	**1.23309**
R_μ	20.785 ± 0.033	20.7423	**1.29256**
R_τ	20.764 ± 0.045	20.7894	-0.565192
A_e	0.1465 ± 0.0032	0.146816	-0.0986973
A_τ	0.1439 ± 0.0041	0.146816	**-0.711178**
A_{FB}^e	0.0145 ± 0.0025	0.0161331	-0.653247
A_{FB}^μ	0.0169 ± 0.0013	0.0161331	0.589909
A_{FB}^τ	0.0188 ± 0.0017	0.0161331	**1.56875**
σ_0	41.54 ± 0.037	41.4746	1.76869
R_b	0.21638 ± 0.00066	0.215673	1.07099
A_{FB}^c	0.0706 ± 0.0035	0.073476	-0.821717
M_W/M_Z	0.777897 ± 0.000658	0.77792	-0.0345382
A_{FB}^b	0.0997 ± 0.0016	0.102903	**-2.0018**
M_t	174.3 ± 5.1	173.131	0.22922
CW (Ces)	-72.84 ± 0.46	-73.1997	0.781884

Sample Parameters

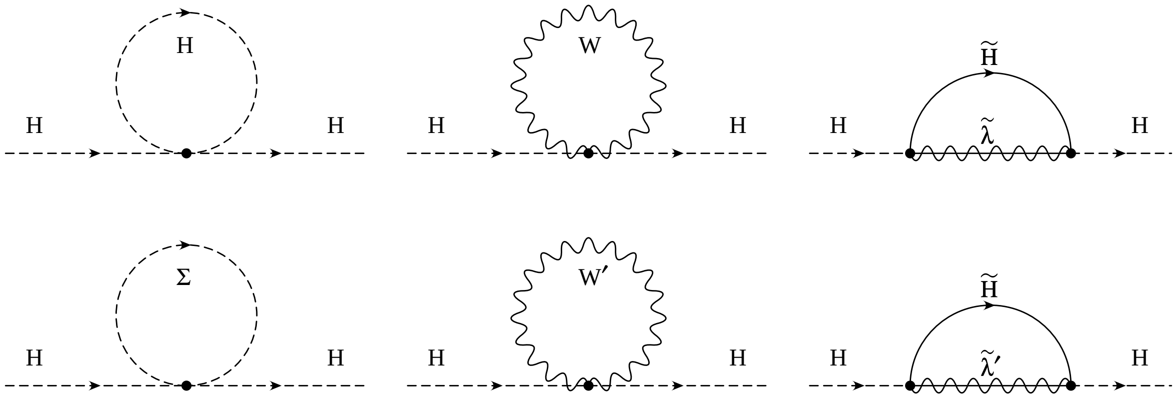
- Let's take some sample parameters:
  - $g_1(u) \simeq 1.6$, $g_2(u) \simeq .8$ (from $g_1(M_G) \simeq 1$).
  - This has $s^2 \simeq .2$.



  - $u \simeq 3$ TeV ($M_{Z',W'} \simeq 2$ TeV).
  - $\tilde{m}_\Sigma \simeq 10$ TeV.
- $\Delta \simeq 7$.
- $m_h \simeq \left(\Delta g^2 + g_Y^2\right) v^2 \simeq 214$ GeV!
- This is easily compatible with the LEP II limit.

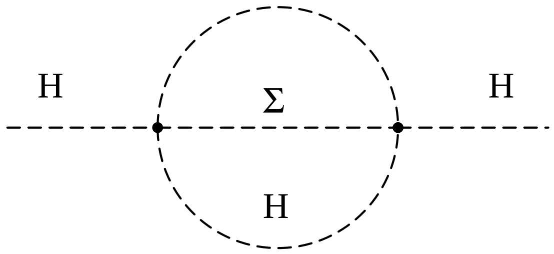
EW Fine-Tuning?

- The presence of a large SUSY-breaking mass for Σ raises the worry that it will feed into $m_{1,2}^2$ and destabilize the weak scale.
- Two contributions to Higgs doublet mass^2:
  - "Hard" SUSY breaking from Higgs quartic:



$$\Rightarrow\ \sim \frac{g^2}{64\pi^2}(\Delta - 1)\tilde{m}_\Sigma^2$$

  - Two loop RGE sensitivity to $\tilde{m}_\Sigma$:

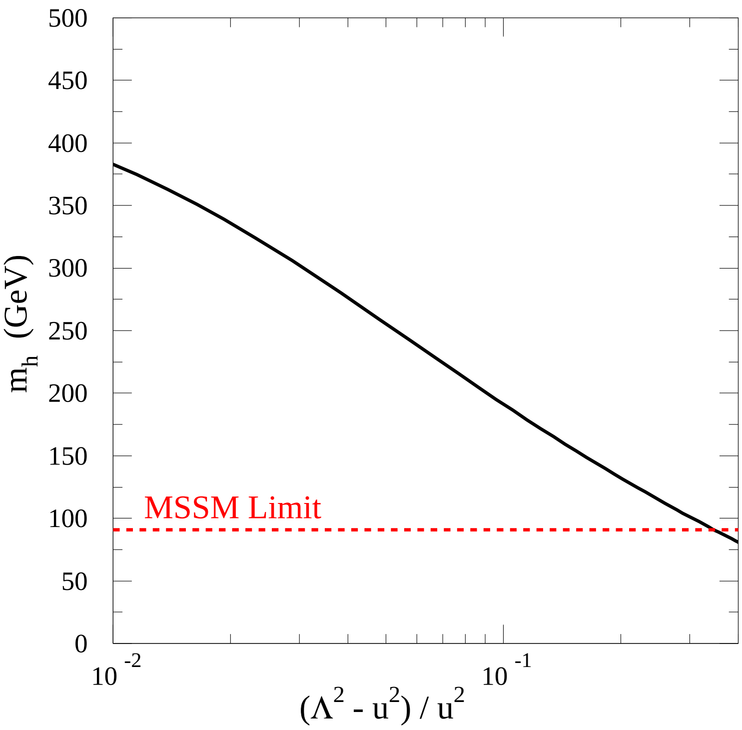


$$\Rightarrow\ \sim \frac{1}{8}\frac{g_1^4}{(16\pi^2)^2}\tilde{m}_\Sigma^2 \log\frac{\Lambda}{u}$$

- Both should be at most of order v^2 itself.
- For $g_1 \sim 1$ and $\Lambda \sim M_{Pl}$ this occurs for $\tilde{m}_\Sigma \lesssim 10$ TeV.

A New Fine-Tuning?

- $SU(2)_1$ is asymptotically free, so we can raise g_1 at u to its perturbative limit: $\alpha_1(u) \sim 1$.
- $s^2 \simeq .05$, $u \geq 3.1$ TeV.
- This allows $\Delta \simeq 20 \Rightarrow m_h \simeq 350$ GeV!
- However, to have $g_1(u)$ maximal, we are effectively tuning two independent parameters: u and the confinement scale Λ_1.
- A (heuristic) way to quantify the fine-tuning is to ask how close u and Λ_1 are for a given m_h:



Complementarity?

- In 1977 Fradkin and Shenker suggested (and found lattice evidence) that there is no phase transition as $SU(N)$ moves from confining to Higgs phase.

- This suggests that perhaps it would be enough to allow $SU(2)_1$ to confine, without explicitly Higgsing it with Σ at Λ_1.

- Composite states with the right quantum numbers to be the third family (and the Higgses) and their super-partners are expected to result.

- They can be thought of as bound states of the scalar Σ bound to a fundamental fermion (or its spartner).

- Any m_h consistent with unitarity would be possible.

- We still need SUSY-breaking at the same scale.

- Maybe something like Affleck-Dine-Seiberg?

- Despite the strong dynamics, gauge coupling unification is affected only at the few per cent level.

Yukawa Interactions

- One immediate problem is the masses for the first and second generations.
- The Higgses are charged under the other $SU(2)$, meaning we cannot write Yukawas directly.
- We introduce copies of the Higgs for $SU(2)_2$:

$$\begin{array}{rcl} SU(2)_1 & : & H_1, H_2, Q_3, L_3 \\ SU(2)_2 & : & Q_1, Q_2, L_1, L_2, H', \bar{H}' \end{array}$$

- H', $\bar{H}'$ can have Yukawas with the first two families.
- We can give this new pair of fields a supersymmetric mass in analogy with the μ parameter of the MSSM:

$$\begin{aligned} W &= \mu' H' \bar{H}' + \lambda' H_2 \Sigma H' + \\ & \quad y_u Q_1 u_1 H' + y_d Q_1 d_1 \bar{H}' + \ldots \end{aligned}$$

- If $\mu' \geq u$, we integrate out the spectator Higgses:

$$y_d \frac{\lambda' u}{\mu'} H_2 Q_1 u_1$$

- If $\lambda' u / \mu' \sim 10^{-2}$ this might explain why charm is so much lighter than top,...

Grand Unification

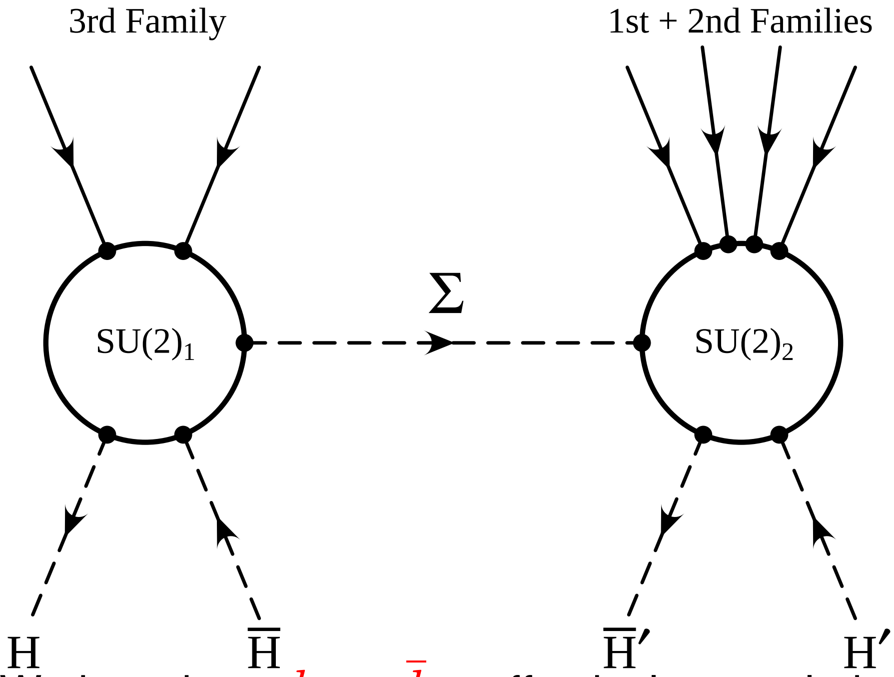
- We can embed our “extra SU(2)” model in a GUT.
- We begin with $SU(5)_1 \times SU(5)_2$ at M_G.
- Each $SU(5)$ has its own GUT coupling g_i.
- Each $SU(5)_i \to SU(3)_i \times SU(2)_i \times U(1)_i$.
- At about the **same** scale, we break $SU(3)_1 \times SU(3)_2 \to SU(3)_C$ and $U(1)_1 \times U(1)_2 \to U(1)_Y$.
- We would like to see under what conditions all low energy couplings are described by both g_i at M_G.
- This requires our two $SU(2)$ couplings to satsify:

$$\frac{1}{g_3^2(M_G)} = \frac{1}{g_Y^2(M_G)} = \frac{1}{g_1^2(M_G)} + \frac{1}{g_2^2(M_G)} = \frac{1}{g^2(M_G)}$$

- The diagonal $SU(2)$ coupling g should unify with g_Y and g_3.

Grand Unification

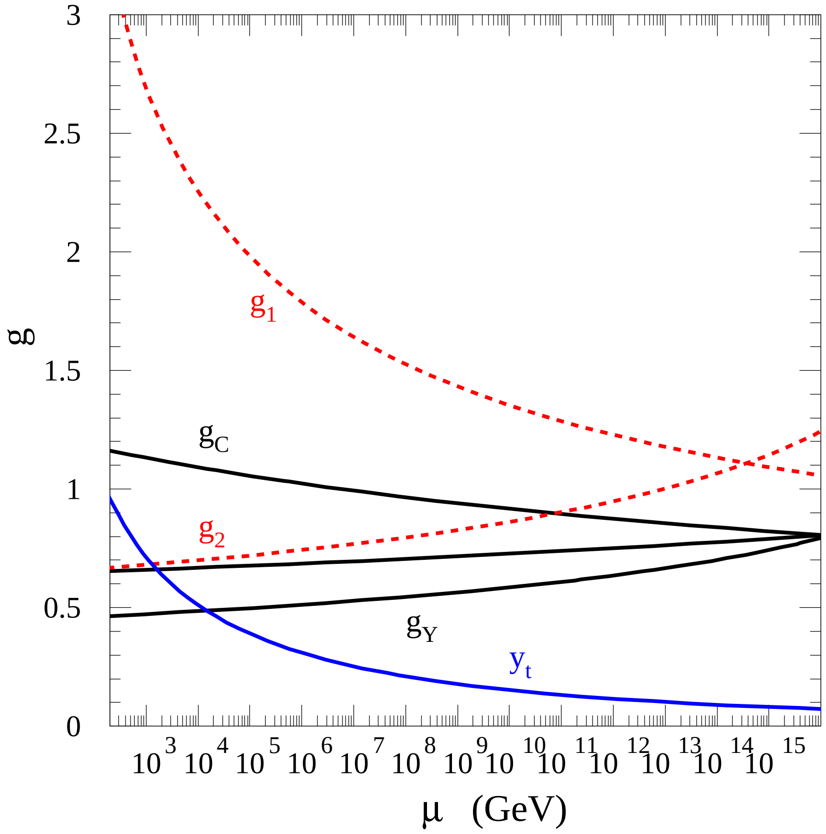
- The extra gauge triplet gives an extra -6 to β.
- This is balanced by adding two triplets to $SU(2)_2$, which could come from adjoints of $SU(5)_2$.
- In addition, the Yukawa interactions for the light fermions required extra Higgs doublets, H', $\bar{H}'$.



- We introduce d_R + $\bar{d}_R$, effectively completing H', $\bar{H}'$ into a 5 + $\bar{5}$.
- The β functions are:
  - $\beta_Y = 38/5$
  - $\beta_1 = -2$ (asymptotically free!)
  - $\beta_2 = 4$
  - $\beta_C = -2$

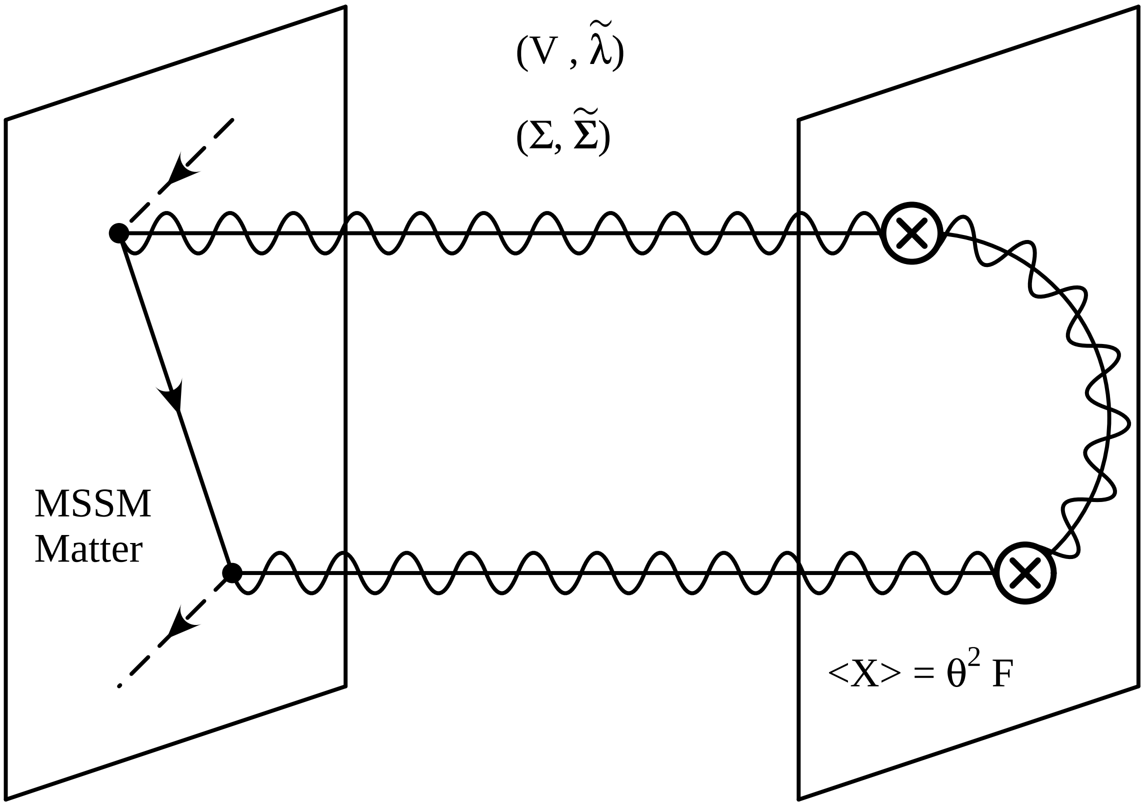
Grand Unification

- As expected, we find unification:



- Red curves: Two $SU(2)$ couplings ($s = 0.2$).
- **Black** curves: Diagonal gauge couplings.
- Blue curve : Top Yukawa ($\tan\beta = 5$).
- The top Yukawa is interesting: the extra strong gauge group driving it small at high energies.
- Perturbative unification is compatible with smaller values of $\tan\beta$ (down to about 0.5).

SUSY Breaking : $\tilde{g}$MSB



- We require a large SUSY breaking for Σ, but MSSM SUSY breaking a few hundred GeV.

- One possibility is $\tilde{g}$-mediation with Σ in the bulk:

$$M_{\tilde{\lambda}} \quad : \quad \int d^2\theta \frac{X}{M_*^2} W^\alpha W_\alpha \, \delta(x_5 - L) \rightarrow \frac{F}{M_*} \frac{1}{M_* L}$$

$$\tilde{m}_\Sigma{}^2 \quad : \quad \int d^4\theta \frac{X^\dagger X}{M_*^3} \Sigma^\dagger \Sigma \, \delta(x_5 - L) \rightarrow \frac{F^2}{M_*^2} \frac{1}{M_* L}$$

- Typically $M_* L \sim 10^2 - 10^3$: $\tilde{m}_\Sigma \lesssim 30 \times M_{\tilde{\lambda}}$

- MSSM sfermion masses through RGE: flavor safe!

SUSY Breaking : AMSB

- Another option is anomaly-mediated SUSY-breaking, with SUSY broken in a sequestered sector which only interacts with gravity.

- SUSY breaking is transmitted gravitationally at loop level through the super-Weyl anomaly.

- We can parameterize SUSY-breaking through the chiral compensator:

$$\langle \Phi \rangle = 1 + m_{3/2}\, \theta^2$$

- The Kahler potential terms for Σ:

$$\int d^4\theta\;\; \Phi^\dagger \Phi \Sigma^\dagger e^V \Sigma \to \int d^4\theta\;\; \bar{\Sigma}^\dagger e^V \bar{\Sigma}$$

- Now consider the term:

$$\int d^4\theta\;\; \Phi^\dagger \Phi \Sigma\Sigma \to \int d^4\theta\;\; \frac{\Phi}{\Phi^\dagger} \Sigma\Sigma$$

- This yields a soft mass for Σ of order $m_{3/2}$.

- MSSM fields occur at loop level, so smaller:

$$\int d^4\theta\;\; \left(1 + \frac{\alpha}{4\pi} \log \Phi^\dagger \Phi\right) \bar{Q}^\dagger e^V \bar{Q} \to m_{\tilde{Q}}{}^2 \sim \left(\frac{\alpha}{4\pi}\right)^2 m_{3/2}^2$$

$$\int d^2\theta\;\; \left(1 + \frac{\alpha}{4\pi} \log \Phi\right) \bar{W}^\alpha \bar{W}_\alpha \to m_{\tilde{\lambda}} \sim \;\frac{\alpha}{4\pi}\; m_{3/2}$$

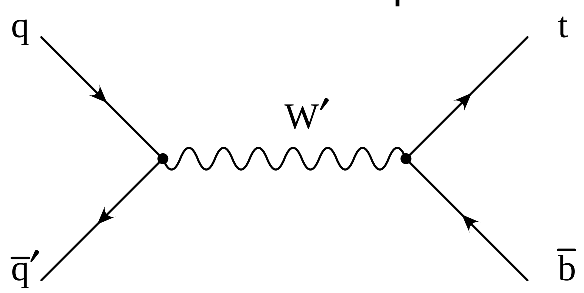
Phenomenology

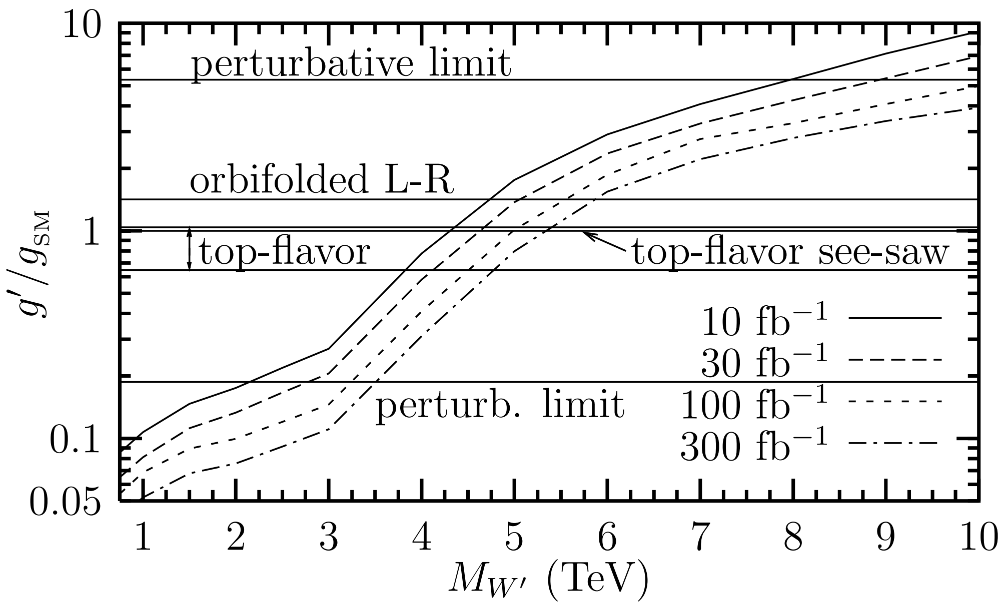
- At energies below a few TeV, our gauge extension has the particle content of the MSSM.
- The new mechanism for m_h allows some super-partners (stops) to be much lighter than the MSSM suggests, increasing discovery odds at run II.
- The key difference is that the Higgs quartic interaction does not take its supersymmetric value.
- It looks like a SUSY theory, but with a hard breaking of SUSY only in the Higgs quartic sector.
- If $m_h \gtrsim 130$ GeV, this will be obvious at the LHC.
- If m_h is compatible with a possible value from the MSSM, it will probably not be evident until the linear collider.
- The hard SUSY breaking will suggest new physics at the 10 TeV scale (or lower).
- This is, of course, provided by the extra gauge bosons (and their gauginos) and Σ fields.

Phenomenology: Gauge Bosons

- We have additional W' and Z' gauge bosons.
- The masses are in the range of a few to 10 TeV.
- The W'/Z' couple preferentially to 3rd-family.
- The LHC can cover much of this parameter space:

[TT, Yuan]





- (Z. Sullivan, hep-ph/0306266).

Phenomenology: Higgs

- Once the Higgs mass is greater than about 150 GeV, decay modes (as in the SM) become quite different.
- Decays into W and Z bosons dominate.
- Provided no SUSY modes open, this is much like the SM, and can be well studied at the LHC.
- $\tan\beta < 1$ is consistent with unification, and enhances couplings to top and charm.
- Neutralinos allow for "invisible" Higgs decays.
- The SM-like Higgs can be quite heavy; it is quite possible that the extra SUSY Higgses will be lighter.
- Decays such as $H^0 \to H^+H^-$ are possible.

Outlook

- The MSSM is in trouble today. It's one firm prediction (a light Higgs) has been excluded.
- This requires EW fine-tuning at the **%** level, to raise m_h above the LEP-II bounds.
- The NMSSM works as an alternative, but doesn't go far because of the desire for unification.
- I have extended the MSSM by an $SU(2)$ gauge group, coupled preferentially to the Higgs and third family.
- This theory is consistent with precision electroweak data, and can be easily engineered into a GUT.
- The Higgs mass may be as high as **350 GeV**!
- Interesting impact on Higgs phenomenology, and results in W' and Z's visible at the LHC.
- Open questions remain, related to SUSY breaking.